ADVANCES IN LASER AND OPTICAL TECHNOLOGIES FOR ROAD STATE DETECTION APPLICATIONS

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ABSTRACT

In this paper we summarize the experiments that have been carried out in the optoelectronic instrumentation laboratory in order to identify the optimum measurement optical technique for remote measurement of the state of the road. The goal of such sensor is to be mounted on board of maintenance vehicles, so robustness and reliability considerations are taken into account in the design of the experiments. That is, the experiments are designed so it would not be a problem to take them out of the laboratory. The states of the road surface that are considered are dry, water and ice and we also monitor residual salt on pavement surface, including when the pavement is dry.

1. INTRODUCCTION

Road maintenance managers increasingly face a perplexing quandary: they are tasked with achieving increasingly strict winter weather mitigation standards, while they are simultaneously under growing pressure to reduce costs, infrastructure damage and environmental impact of operations. The answer to this dilemma lays on the precise detection of road conditions and the impact of maintenance actions, those being the safest way to optimize equipment and material usage such as snowplows and anti-ice & snow chemicals.

Due to the extent of networks and the problems associated to deploying enough stationary detection points to fully characterize them (cost, communications…), mobile detection technologies are the most elegant solution to receive comprehensive network data [1]: they can provide instant and reliable local information about weather parameters such as temperature and humidity, as well as road parameters such as surface temperature or ice presence.

The first challenge in receiving real time information from mobile systems is communications, but mature technologies are already available and used by maintenance agencies. Sensor technology and on-board sensor information fusion, on the other hand, are still in research and development phase, with very few and expensive commercial solutions available. Mobile road weather systems, after all, impose severe technical constrains that difficult implementation (resistance to corrosion, robustness against vibration and impacts, the capacity to measure at regular circulation speed,…).

Technologies for on-board remote sensors based on optics remain a very promising avenue: optical sensors are able to detect the presence of specific substances by analyzing the change of the properties of an optical beam that is reflected by or transmitted in a medium, and this can be made in real-time. Possible applications include visibility measurement, tunnel air-opacity evaluation for smoke detection, lidar systems for distances and speed, or road-surface assessment. In the latter case, water and ice sensors have been reported based on infrared spectroscopy [2] and light polarization [3], and salinity measurements have been reported based on Raman spectroscopy [4] and fluorescence spectroscopy using salt treated with additives [5]. These techniques are also successfully used in other instrumentation systems for industrial, medical and environment applications.

In this work we propose and evaluate the use of optical sensors using semiconductor light sources to provide information of the state of the pavement and the residual salt on pavement surface at the same time. The main advantages of semiconductor light sources, such as laser diodes and LEDs, are their availability at low cost and at a large (and every day increasing) range of wavelengths, ranging from the ultraviolet (around 400 nm and lower) to the infrared, traditionally below 2000 nm, but laser diodes up to 14 µm are commercially available nowadays.

In this paper we focus on the description of the experiments that have been carried out by the optoelectronic instrumentation laboratory at Carlos III University of Madrid. The main goal of the experiments has been to explore the application of semiconductor light sources for the remote measurement of the state of the road due to meteorological phenomena and winter maintenance activities. The relevant information in this case is if the road is dry or not, if there is a layer of water, or ice or snow, the temperature of the asphalt and the freezing point temperature. The measurement of the freezing point temperature is an indirect measurement of the amount of residual anti-icing chemical, so we consider in this study to measure directly the presence of salt, as it is the most frequently used anti-icing chemical.

The paper is divided as follows: In the next section we describe the basic theory and the experimental set-up that has been used is the laboratory. The third section presents two different alternatives to distinguish the presence of ice or water on a road surface. The fourth section shows the proof of concept of an optical sensor for remote measurement of the amount of residual salt on dry pavements. We finish with conclusions and further research.

2. BASIC OPTICAL SCHEME FOR ‘STATE OF THE ROAD’ REMOTE SENSORS

The proposed technique for remote sensing of water, ice and other substances on the pavement surface is based on diffuse reflectance spectroscopic techniques combining the use of semiconductor light sources and lock-in detection techniques. When a beam of light hits a surface of a material, part of the light is reflected back. This reflection is a mixture of specular reflection (with the same angle than the incident beam) and diffuse reflection, with out-coming beams in all directions. Diffuse reflection is due to transmitted light into the material that change direction of propagation (scatters) due to the presence of particles inside the material, which then eventually comes out of the same surface at an arbitrary direction of propagation. This can be seen in Figure 1. Diffuse reflectance is the optical effect that, for example, makes the snow look white despite being composed of small ice crystals which are transparent: that is, they do not absorb any colour but ice crystals scatter all the colours of light in all directions and thus the observer sees white light [6].

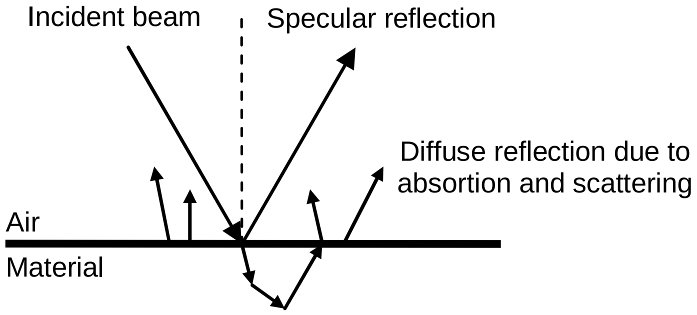

Figure 1. Specular and diffuse reflection on the surface of a material

The amount of light that is diffuse reflected depends on the optical properties of the material: It depends on the real part of the refraction index of the material (n), which limits the amount of transmitted light into the material. It depends on the imaginary part of the refraction index of the material (K) which is proportional to the absorption coefficient that quantifies the attenuation of the light intensity when propagating through the medium. It also depends on the scattering coefficients. All these optical properties of the material are not constant but depend on the wavelength of the illumination beam. As an example Figure 2 shows the imaginary part of the refraction index for water and ice as a function of the illumination wavelength in a portion of the near infrared region of the spectrum. We can see in this figure two peaks of absorption for the ice at wavelengths 1500 nm and 2000 nm approximately. The water also present two absorption peaks but slightly shifted in wavelength.

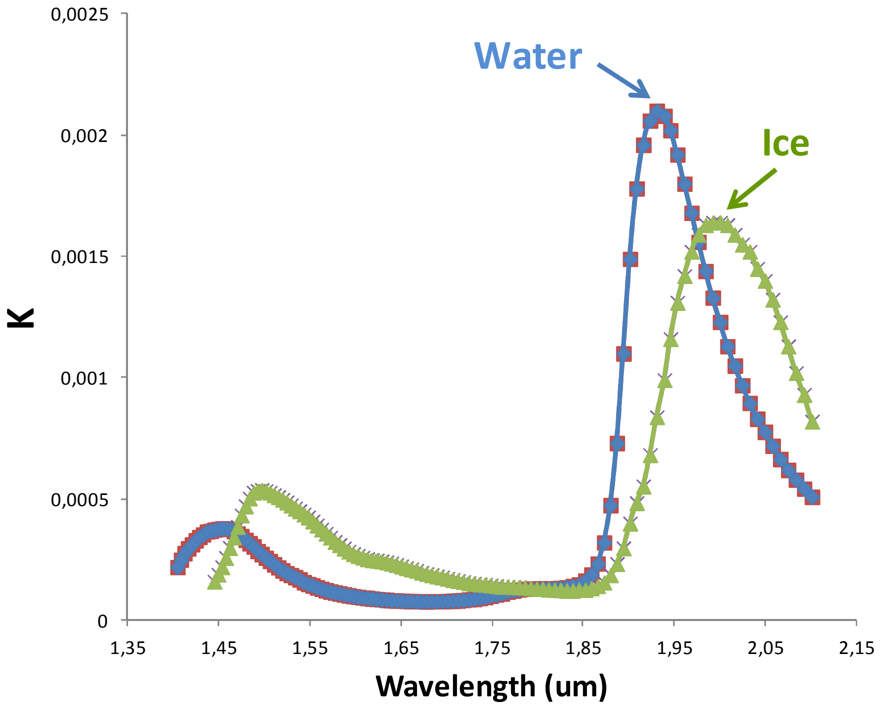

Figure 2. Imaginary part of the refraction index of water and ice as a function of wavelength (data for the figure have been extracted from [7])

As the reflection spectrum is a characteristic of the material it is possible to identify the presence of a specific substance by analyzing its reflection spectra. Typical spectroscopic systems use wide-spectrum light sources (as a xenon lamp) and, with the aid of diffraction gratings and complex opto-mecanical systems, either on emission or on detection, the spectral decomposition is made. Due to the fact that mobile road state and weather sensors impose severe technical constrains that difficult implementation (resistance to corrosion, robustness against vibration and impacts and the capacity to measure at regular circulation speed…) we propose not to use such complex optical systems and use semiconductor light sources-based systems instead that make it possible to avoid the use of opto-mechanical systems (for which maintaining alignment can be complex).

Semiconductor light sources present two main advantages for building remote optical sensors. The first one is that they emit monochromatic light (one color): their emission spectrum is centred at a specific wavelength with a spectral width of around 40 nm in the case of LEDs and as narrow as 0.01 nm in the case of laser diodes. The second advantage is that their output light intensity can be modulated at high speed using electronic circuits and thus high sensitivity detection techniques, as lock-in detection, can be used to avoid the influence of ambient illumination and increasing resolution. Taking these considerations into account we have designed several experiments to test the feasibility of using semiconductor lasers to identify the state of the road in a mobile system.

The simplified scheme for all the experiments is shown in Figure 3. It consists of one or several semiconductor light sources that illuminate a pavement surface at a constant distance. A lens makes the illumination area remain constant. We will see that in most of the experiments the source's wavelength is in the infrared range. The output light intensity is amplitude modulated with a sinusoidal signal using a signal generator. The modulation index (ratio between maximum and minimum amplitudes) is always kept near 100% and the frequency is in the range of a few tens of KHz. In this figure is also shown the single photodiode that measure diffuse reflection from the test surface (regardless the number of wavelengths used) and after proper amplification, a lock-in amplifier performs synchronous detection using as a reference the modulation signal, this detection technique allows that only the diffuse reflected light from the emitter is measured. Both commercial lock-in amplifiers (Stanford Research Systems SR830) and custom implementations developed in our laboratory have been used to perform the detection. The test sample surface is typically a piece of asphalt that is kept dry or with water, ice or salt on it.

Figure 4 shows a picture of one of the typical experiments. Here we can see the surface under test covered with water that is inserted inside a climatic chamber that allows to change ambient conditions (temperature and relative humidity) so ice is formed when lowering temperature below 0ºC. The photodiode is also introduced in the climatic chamber and the illumination beam is introduced using an optical fibre, so laser diodes are kept outside the climatic chamber. In the pictures we can see the tube mounts that hold the optics of emitters and the detector.

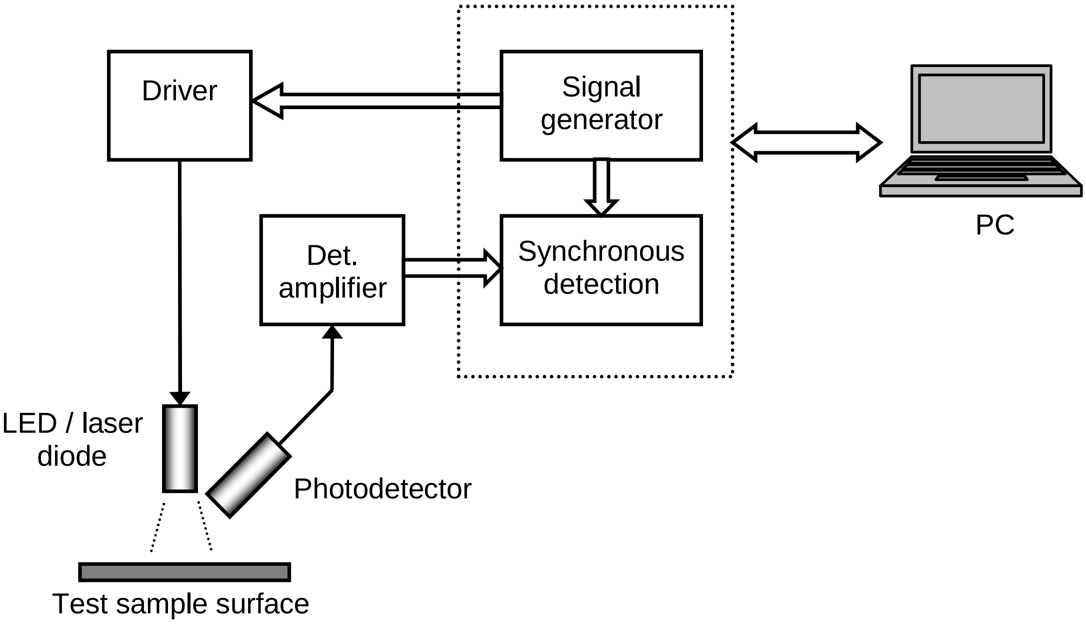

Figure 3. Basic optical scheme for state of the road sensors

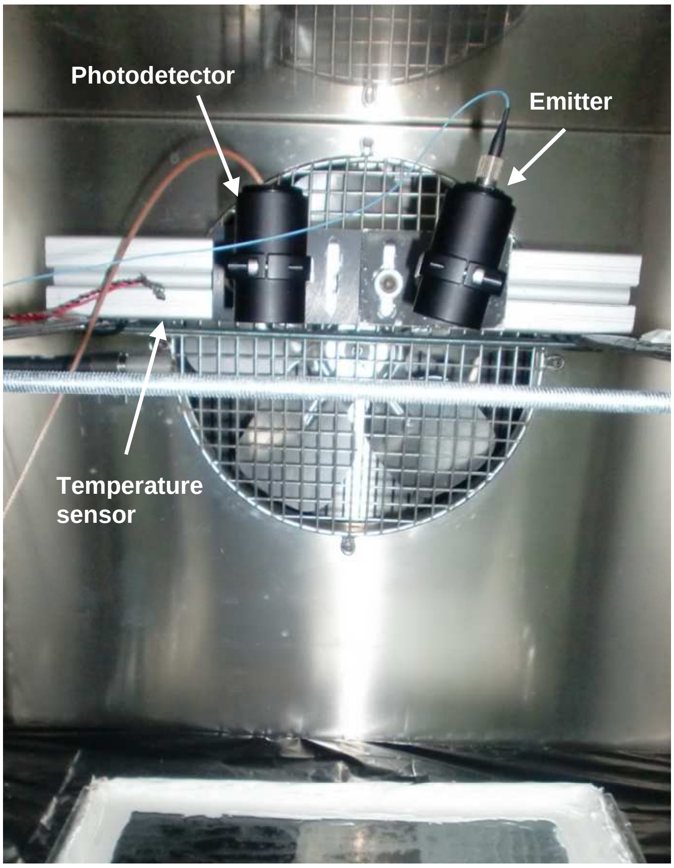

Figure 4. Picture of one of experiments in a climatic chamber

3. DISTINCTION OF WATER AND ICE BASED ON BIRREFRINGENCE

Birefringence is an optical property of some materials in which the refraction index (n) depends on the direction of propagation of the light and also on its polarization (orientation of the oscillation of the optical waves). As the amount of reflected light depends on the refraction index, in a birrefringent material the amount of light reflected back depends on the observed polarization. In the application of determining the state of the road this property can be used to distinguish the presence of water or ice [3] because liquid water does not present birefringence but ice does.

To perform this experiment we used, as the emitter, a laser diode model DL-5032 from Sanyo which emits at 830 nm (infrared) and keep predominant polarization with the help of a polarizer. We also include an additional photodetector as is represented in Figure 5. In front of each photodetector we place a polarizer so each of them is receiving light at different state of polarization. The polarizers of the detectors are placed in perpendicular directions between them and both at 45º to the direction of the emitter polarizer. The results of the experiment are represented in Figure 6. The upper trace in the figure represents the temperature inside the climatic chamber. We can see two cooling/heating cycles of more than an hour each, so giving enough time to freeze a film of water on the test surface. The lower trace shows the ratio between the output light intensity that is measured with each receiver (cross polarized light). Shadowed regions show the time intervals in which there is only liquid water or there is only frozen water (ice). In these regions the ratio for water and ice is different so we can conclude that the effect of birefringence can be used to distinguish between water and ice on a pavement surface using an optical sensor based on a semiconductor laser source (LED or laser diode). We also appreciate in Figure 6 some undesirable effects that we have concluded are due to condensed water on the surface of the optical components.

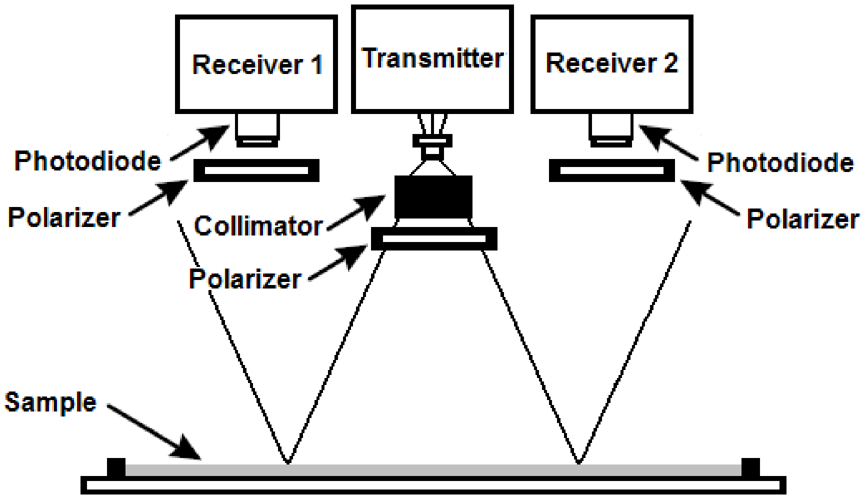

Figure 5. Experimental setup for ice birefringence measurements

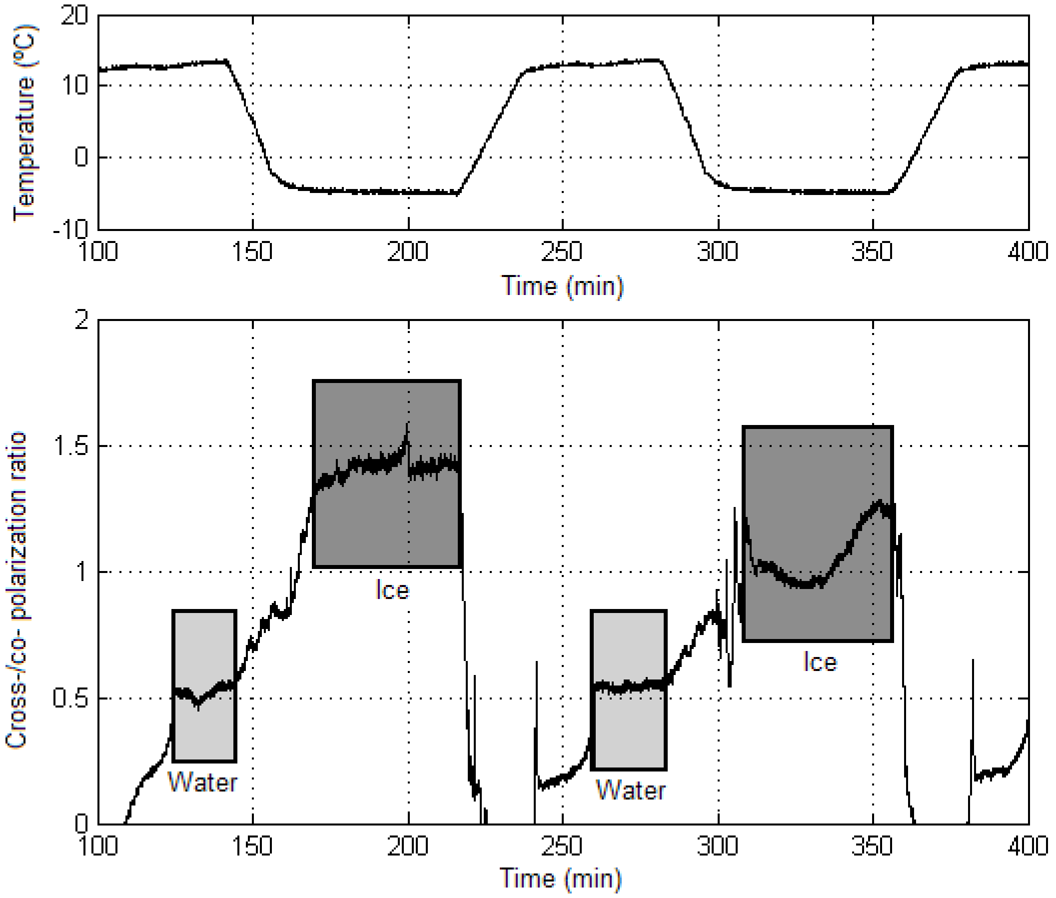

Figure 6. Results for ice/water identification based on birefringence measurements. Liquid and solid phase are clearly distinguishable.

4. DISTINCTION OF ROAD STATES BASED ON DIFFERENTIAL ABSORPTION COEFIENTS

Using the same scheme described previously, we are going to explore in this section the wavelength dependence of the complex refraction index in the near infrared of different substances of application to remote road state sensors. The presence of water on the surface of the road and the thickness of the water layer varies the amount of diffuse reflection, so it is possible to identify the state of the road (dry or wet) just lighting an area of the road and measuring the reflected light. The wavelength dependence of the optical properties of water is different depending on its state, liquid or solid (ice), so spectroscopic characterization of the reflected light gives much more information about the state of the road.

One of the most important issues associated to the design of this type of sensors is wavelength selection. The optical properties of water and ice have been widely studied for many years [7], and we have used these studies to select the most convenient wavelengths for our application. In the near infrared, the real part of the refraction index (n) is approximately constant with wavelength, while the imaginary part (K), related with the absorption coefficient, shows peaks at determined wavelengths. Those peaks are slightly displaced in wavelength for water and ice. Moreover, one of those peaks is centered close to 1550 nm (see Figure 2). At this wavelength, as it is one of the main optical communication windows, lasers and fiber optic components are commercially available at low cost. At 1310 nm, the other main optical communication window, the imaginary part of the refraction index is in a minimum both for water and ice. In this sense, and to test the sensing principle, we used standard DFB pigtailed semiconductor laser diodes at 1310, 1470 and 1550 nm. Those emitters are combined into a single fiber with a standard 1310/1550 nm fibre optic coupler so the illuminating area is the same for the three emitters (see picture in Figure 4).

The system has been calibrated using a climatic chamber. Figure 7 shows some examples of the sensor output provided by the lock-in amplifier. The blue trace (bottom trace) is a signal proportional to the light detected at 1550 nm. The green trace (upper trace) is proportional to the ratio between the light detected at 1310 and 1550 nm. The red trace (in the middle) is proportional to the ratio between the light detected at 1310 and 1470 nm. It can be seen that although the optical power detected at a determined wavelength (ie. 1550 nm) is not constant, ratios are constant for a specific substance (water or ice). The distance between those ratios depends on the substance that is present and thus the information about the state of the road can be obtained from these signals.

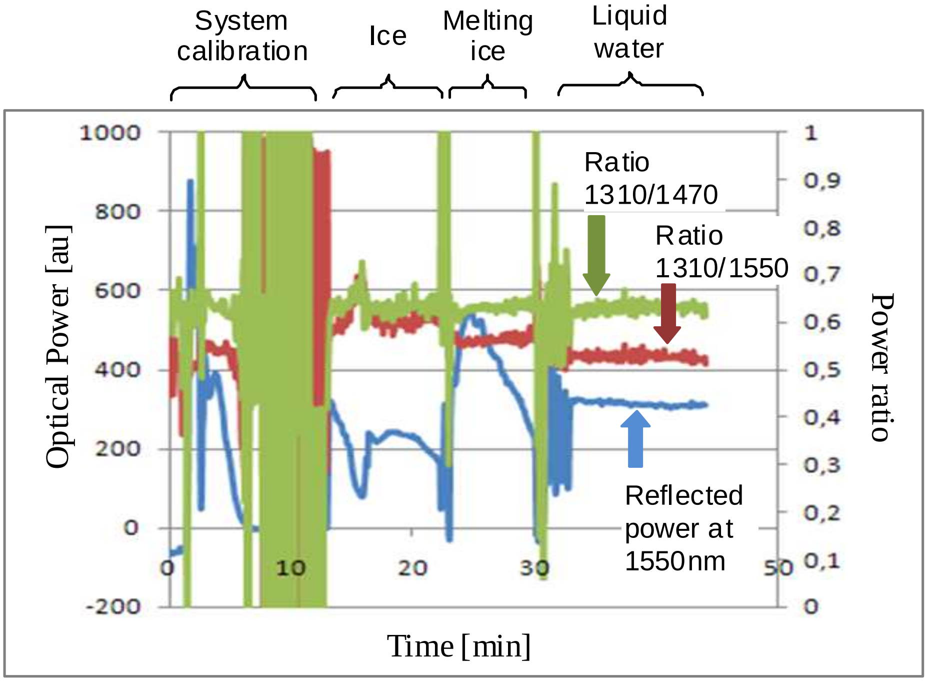

Figure 7. Output signals of the experiment based on differential absorption

Many experiments for measurement the state of the road has been carried out using this measurement principle. We have varied the temperature of the pavement surface, the thickness of the water and ice layers and the distance of the sensor to the surface. The summary of the results is represented in Figure 8. In this figure the horizontal axis is the ratio between the light detected at 1470 nm and 1310 nm, the vertical axis is the ratio between the light detected at 1550 nm and 1310 nm. In this figure we can see clusters of data each corresponding to a different condition of the road surface. Points with a blue diamond correspond to dry pavement, points with a green triangle correspond to wet pavement and points with orange balls corresponds to icy pavement surface. From this results it is clear that using this optical technique it is possible to separate the different road states.

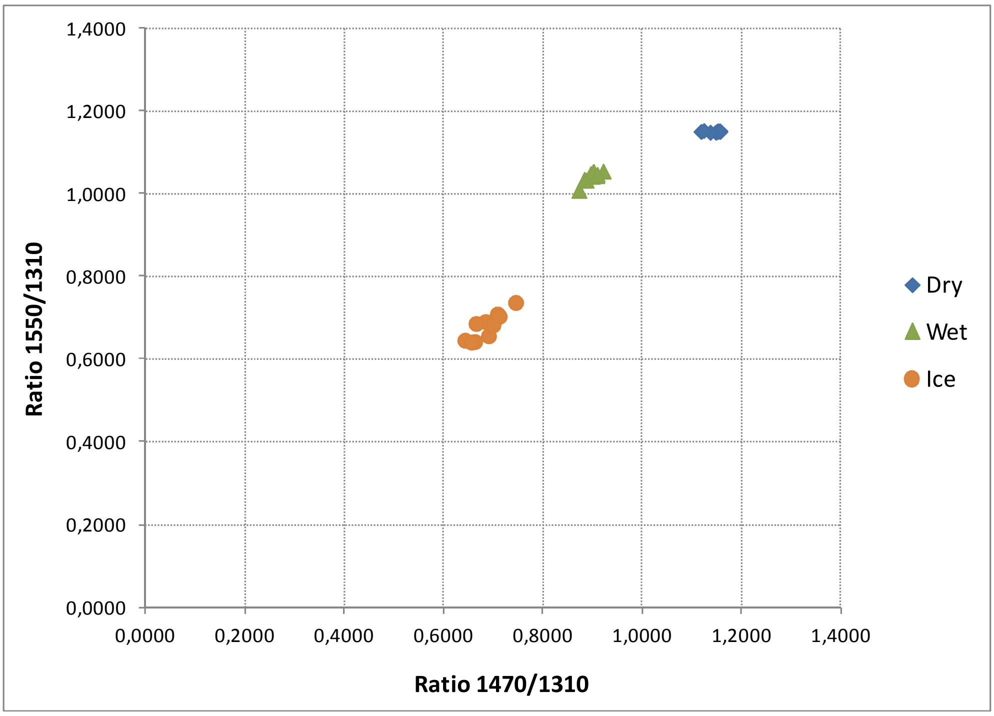

Figure 8. Road states classification based on differential absorption measurements
Clusters of data correspond to different road states

5. IDENTIFICATION OF SALT ON ROAD SURFACE BASED ON FLUORESCENCE

Another very interesting parameter that determines the state of the road during winter campaigns is the presence of residual salt from previous anti-icing winter maintenance activities. The monitoring of residual salt is useful to prevent over-salting and its economic and environmental consequences.

It is known that the index refraction of a salt solution varies the refraction index proportional to the concentration. We have tried to use this measurement principle with the remote system set up represented in Figure 3 but the results obtained have not been conclusive. Additionally such a sensing principle is not useful in dry pavement where we need to measure the amount of residual dry salt, because the optical properties of this substance are almost constant with wavelength and polarization.

Other promising remote optical techniques for residual salt monitoring are induced fluorescence [5], Raman spectroscopy [4], and laser induced breakdown spectroscopy [1]. Considering on-board measurements, the first one, induced fluorescence, has several advantages compared with the other above-mentioned spectral techniques. First there is no need of critical spectral discrimination optical hardware, such as grating spectrometers that are difficult to maintain aligned, as excitation and emission wavelengths are far from each other, thus reducing the risk of measurement errors due to optical instrument misalignment. Second, there is no need of high intensity and pulsed laser sources, being safe for operators and users.

Fluorescence is an optical phenomenon in which the material absorbs light at specific wavelength and reemits light at a different longer wavelength. Salt (NaCl) crystals present natural fluorescence due to impurities or lattice imperfections, so in this work we propose to exploit the natural fluorescence of the salt but it would be also possible to exploit the fluorescence of road salt additives, as has been proposed earlier [5].

To evaluate the feasibility of a sensor system based on natural salt fluorescence the luminance properties of different salt samples has been studied. In this sense, the emission spectrum of table salt, marine salt, which is used for brine preparation, and rock salt used for anti-icing and de-icing road treatments are presented below. The different salt samples were analyzed using a F900 Edinburgh Fluorimeter, with a range between 200 nm to 900 nm, equipped with a fiber optic bundle for back emission fluorescence measurements. The fiber optic was placed at a distance of 4 mm from the sample and the excitation-emission maps where taken in the full range of the flourimeter for the three types of salt. These maps represent in a three dimensional plot the light intensity measured at a specific emission wavelength λ_{em} when illuminating the sample at specific excitation wavelength λ_{exc}. All the maps showed maximum light intensity at emission wavelengths λ_{em} = 310 nm and λ_{em} = 610 nm, both for excitation wavelength around λ_{exc} = 270 nm. Figure 9 shows relevant results in a two dimensional plots. It represents the measurement of the emission spectrum with excitation wavelength λ_{exc} = 273 nm for three different salt types, in this figure emission peaks at 310 nm and 610 nm are clearly identified. This strong fluorescence in the red region of the visible spectrum can be used as an indicator of the amount of salt spread in a surface.

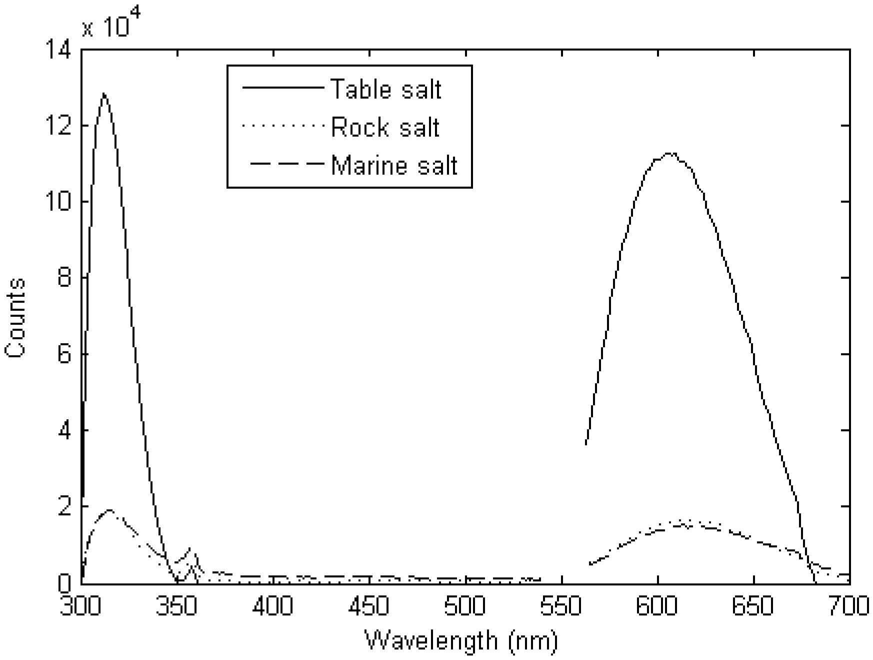

Figure 9. Emission spectrum of salt when illuminated at λ_{exc} = 273 nm

To test the feasibility of a sensor for residual salt monitoring based on fluorescence we also used the set-up represented in Figure 3. In this case we used an ultraviolet LED source (UVTOP275) with emission spectrum centered at 275 nm and a red filter in front of the photodetector so the fluorescence at 610 nm is measured. In this system specific detection techniques have been developed taking into account the fluorescence decay time. This system was tested against several scenarios composed of different dosages of dry salt homogeneously distributed over the test sample surface. Taking into account that usual preventive anti-icing road treatments have a maximum salt concentration of about 15 g/m^2, several samples using five different salt dosages from 0 to 20 g/m^2 were prepared and analyzed with the developed sensor. The results of these measurements are shown in

Figure 10 where it is important to note that part of the uncertainty associated to the different points in the measurement is due to dispersion on the different samples preparation and uneven salt distribution over the surface for the different realizations. As we can see from this figure, uncertainties in the range of 2 g/m^2 are typical, while being able to measure salt dosages below the required limits (15 g/m^2).

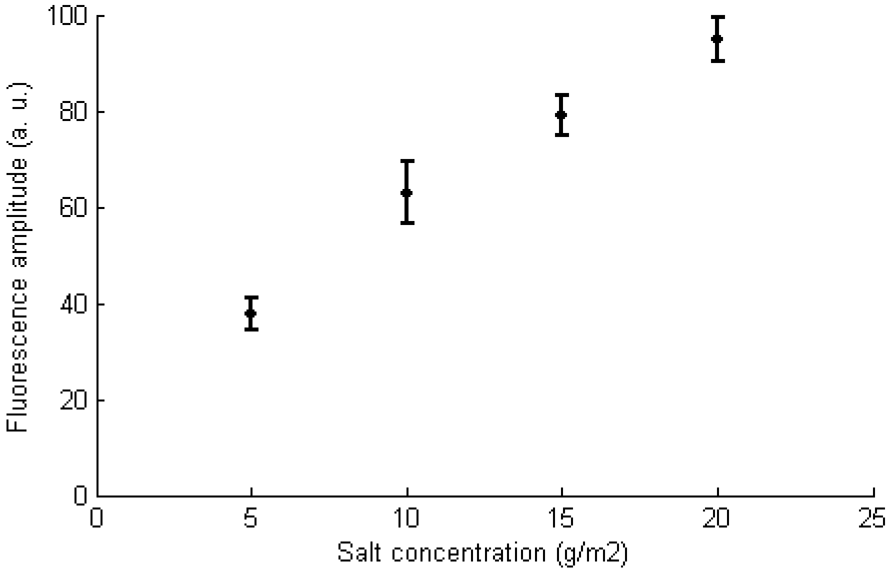

Figure 10. Results of dry salt dosage measurements based on fluorescence. Linear relationship between measurements and amount of residual salt

6. CONCLUSIONS

In this paper we have investigated different techniques for the implementation of an optical remote sensor for the measurement of the state of the road. The goal is to develop a robust sensor system set-up that can be monitoring the road surface when mounted on a maintenance vehicle. As critical opto-mechanical components need to be avoided in a mobile system, we exploit the characteristics of semiconductor light sources, which are narrow spectral bandwidths and direct intensity modulation in combination with lock-in detection using electronic circuits.

The conclusions of our investigation, whose main contributions are summarized in this paper, is that diffuse reflection spectroscopic technique based on infrared laser diodes is optimum for the development of a remote mobile sensor to determine the state of the pavement [8]. We show that low cost communication laser diodes gives good classification results for the road state. We believe that the results can be improved (in terms of resolution and optical power required for the emitters) if other specific illumination wavelengths are used to develop such a sensor.

We also conclude that same technique is difficult to expand to residual salt monitoring especially if the pavement is dry. In this case we show in this paper that it is possible to exploit the natural fluorescence of the salt (or fluorescence of additives in anti-icing subtanteces) to determine the amount of residual salt from previous anti-icing treatments.

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